



Review

Chemical hazards associated with treatment of waste electrical and electronic equipment

Oyuna Tsydenova, Magnus Bengtsson *

Institute for Global Environmental Strategies, 2108-11 Kamiyamaguchi, Hayama, Kanagawa 240-0115, Japan

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ABSTRACT

This review paper summarizes the existing knowledge on the chemical hazards associated with recycling and other end-of-life treatment options of waste electrical and electronic equipment (e-waste). The hazards arise from the presence of heavy metals (e.g., mercury, cadmium, lead, etc.), flame retardants (e.g., pentabromophenol, polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol-A (TBBPA), etc.) and other potentially harmful substances in e-waste. If improperly managed, the substances may pose significant human and environmental health risks. The review describes the potentially hazardous content of e-waste, examines the existing e-waste management practices and presents scientific data on human exposure to chemicals, workplace and environmental pollution associated with the three major e-waste management options, i.e., recycling, incineration and landfilling. The existing e-waste management practices and associated hazards are reviewed separately for developed and developing countries. Finally, based on this review, the paper identifies gaps in the existing knowledge and makes some recommendations for future research.

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* Corresponding author. Tel./fax: +81 468553843/709.

E-mail address: bengtsson@iges.or.jp (M. Bengtsson).

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1. Introduction

Discarded electrical and electronic products (often called e-waste) is one of the fastest growing waste streams and it has been estimated that these items already constitute 8% of municipal waste (Widmer et al., 2005). The increasing volumes of e-waste, in combination with the complex composition of these items and the resulting difficulties in treating them properly, are causes of concern. The hazardousness of e-waste is well recognized, but the knowledge on these hazards and the resulting risks associated with different treatment options is currently fragmented. Therefore, a survey of the available scientific literature was conducted in order to gather the hard data on workplace and environmental pollution, human exposure to chemicals and resulting adverse effects due to recycling, incineration and landfill disposal of e-waste. This review paper summarizes the current knowledge on these issues, identifies knowledge gaps and points out key areas where further research would be beneficial.

The paper begins by an overview of the components and substances that are frequently found in e-waste and that may be of concern from an environmental and health perspective. It then moves onto reviewing first the current situation on e-waste treatment in developed countries and the knowledge on associated risks, and second the conditions in developing countries. A concluding section highlights some of the key findings of the study and makes recommendations on future research.

2. Components and hazardous substances in e-waste

Electrical and electronic equipment can contain a large number of hazardous substances, including heavy metals (e.g., mercury, cadmium, lead, etc.), flame retardants (e.g., pentabromophenol, polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol-A (TBBPA), etc.) and other substances. Due to the presence of these substances, e-waste is generally considered as hazardous waste, which, if improperly managed, may pose significant human and environmental health risks.

There are certain common components/parts of electrical and electronic appliances that contain the majority of the hazardous substances (Table 1). The following components are considered to be the most hazardous.

2.1. Mercury-containing components

Mercury is used in relays (used in telecommunication circuit boards, commercial/industrial electric ranges, and other equipment) and switches (used in a variety of consumer, commercial, and industrial products, including appliances, space heaters, ovens, air handling units, security systems, leveling devices, and pumps), batteries, and gas discharge lamps (used for backlighting in liquid crystal displays in a wide range of electronic equipment, including computers, flat screen TVs, cameras, camcorders, cash registers, digital projectors, copiers, and fax machines) (NEWMOA, 2008).

2.2. Batteries

From an environmental perspective, mercury containing batteries and rechargeable batteries containing cadmium, lead and lithium are of concern (EPS Canada, 2006). Rechargeable batteries include nickel cadmium (Ni–Cd), nickel metal hydride (NiMeH), lithium ion and lead acid batteries and are commonly used in portable (notebook/laptop) computers, mobile phones, video cameras, portable power tools, etc.

2.3. Printed circuit boards (PCBs)

PCBs contain a number of substances of concern (AEA, 2004; EPS Canada, 2006; OECD, 2003). These are lead (in solder), antimony (in solder), beryllium (in connectors), cadmium (in contacts and switches), brominated flame retardants (in plastics), etc. The flame retardants used in PCBs are TBBPA and PBDEs. Besides the hazardous substances, PCBs contain a substantial quantity of copper and valuable concentrations of gold, silver and palladium. Individual solid state devices, such as mercury relays and switches, capacitors and light emitting diodes, may also be present in PCBs, i.e., attached to the boards.

2.4. Cathode ray tubes (CRTs)

CRTs contain the greatest amount of all substances of concern in older desk top computers and TV sets. An older polychrome CRT can contain 2–3 kg of lead, while a more recent one typically contains no more than 1 kg of lead. The inside of CRT panel is coated with fluorescent phosphors composed of cadmium, zinc and rare earth metals. The electron gun of the CRT contains a small getter plate, weighing approximately 1–2 g including frame and bears barium and barium compounds (OECD, 2003).

Table 1

Overview of the hazardous components and substances commonly found in WEEE.

Components	Found in	Substances of concern
Cathode ray tubes	Old TV sets, PC monitors, oscilloscopes	Pb in cone glass Ba in electron gun getter Cd in phosphors
Printed circuit boards	Ubiquitous, from beepers to PCs	Pb, Sb in solder Cd, Be in contacts Hg in switches BFRs in plastics
Batteries	Portable devices	Cd in Ni–Cd batteries Pb in lead acid batteries Hg in Hg batteries
Gas discharge lamps	Backlights of LCDs	Hg in phosphors
Plastics	Wire insulation, plastic housing, circuit boards	PVC BFRs

2.5. Liquid crystal displays (LCDs)

LCDs are used in a wide variety of applications. Liquid crystals are embedded between thin layers of glass and electrical control elements. A cellular phone display can contain about 0.5 mg of liquid crystals, a notebook PC display about 0.5 g. Commercially available liquid crystals are mixtures of 10–20 substances, which belong to the groups of substituted phenylcyclohexanes, alkylbenzenes and cyclohexylbenzenes. About 250 substances are used for formulating more than a thousand marketed liquid crystals. The substances contain oxygen, fluorine, hydrogen and carbon. The liquid crystals are suspected to be hazardous, but studies on their toxicity are scarce. So far conducted studies have not found

carcinogenic potential and acute oral toxicity, although a few substances showed corrosive, irritant or sensitizing properties to the skin (AEA, 2004).

2.6. Plastics containing brominated flame retardants (BFRs, in various plastic parts) and plastics made of polyvinylchloride (PVC, in wire insulation)

Plastics make up a significant constituent of e-waste by weight, about 30% plastics (Schlummer et al., 2007). PVC is one of the most widely used in electrical and electronic equipment polymers, often as insulation coating on wires and cables. The reason for concern is the presence of chlorine in PVC and, thus, potential to yield

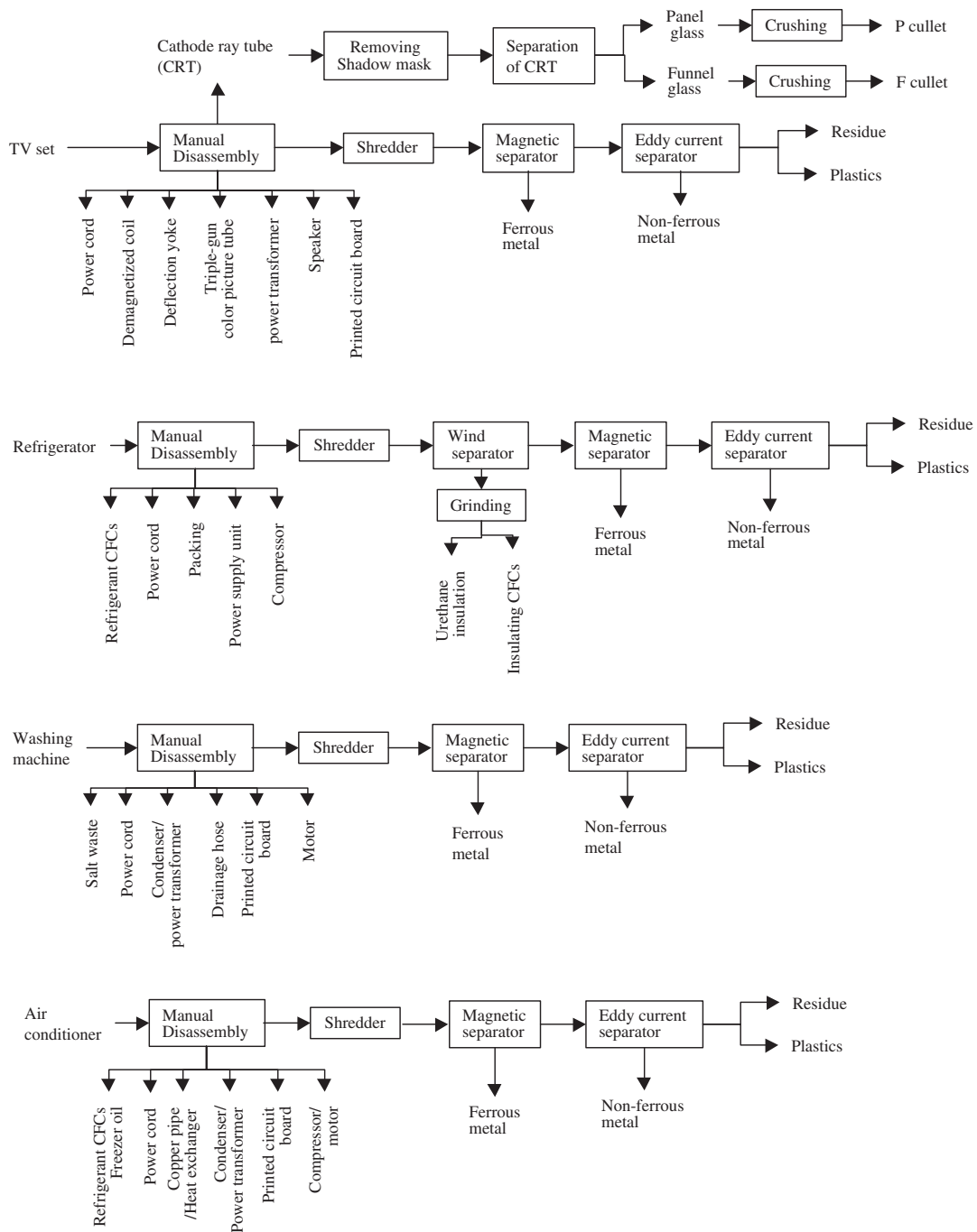


Fig. 1. Process flow in a Japanese recycling facility. Reproduced from Matsuto et al. (2004) with permission from Elsevier.

polychlorinated dibenzo-*p*-dioxins and furans (PCDDs/Fs) during uncontrolled burning. Concerns have also been raised about the use of metals, particularly cadmium, as stabilizers and phthalates as plasticizers in PVC.

BFRs are another group of chemical additives used not only in PVC but also in other types of plastics. BFRs are used to reduce the flammability of commercial products and are found in PCBs, cables, plastic covers of computers and TV sets, and other products (Birnbaum and Staskal, 2004). Two primary families of BFRs have been used in electrical and electronic equipment. The first family is PBDEs, which are mainly used in cabinets. The second family of BFRs is the phenolics, which includes TBBPA, used primarily in PCBs (AEA, 2004).

3. Hazards and risks associated with e-waste treatment in developed countries

Presence of hazardous substances in electrical and electronic equipment inevitably links its end-of-life disposal with the potential risks to human health and the environment. This section examines the existing e-waste management practices and associated chemical hazards in developed countries.

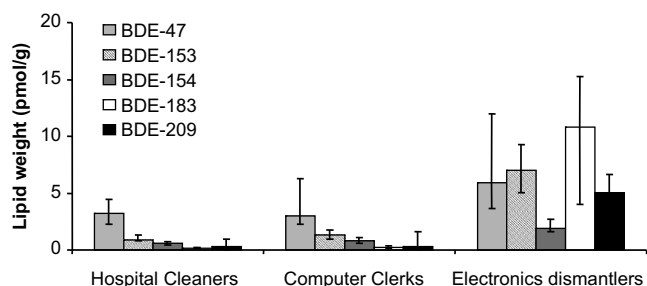


Fig. 2. Median concentrations (pmol/g lipid weight) of five polybrominated diphenyl ether congeners in the study groups. Reproduced from Sjödin et al. (1999) with permission from Environmental Health Perspectives.

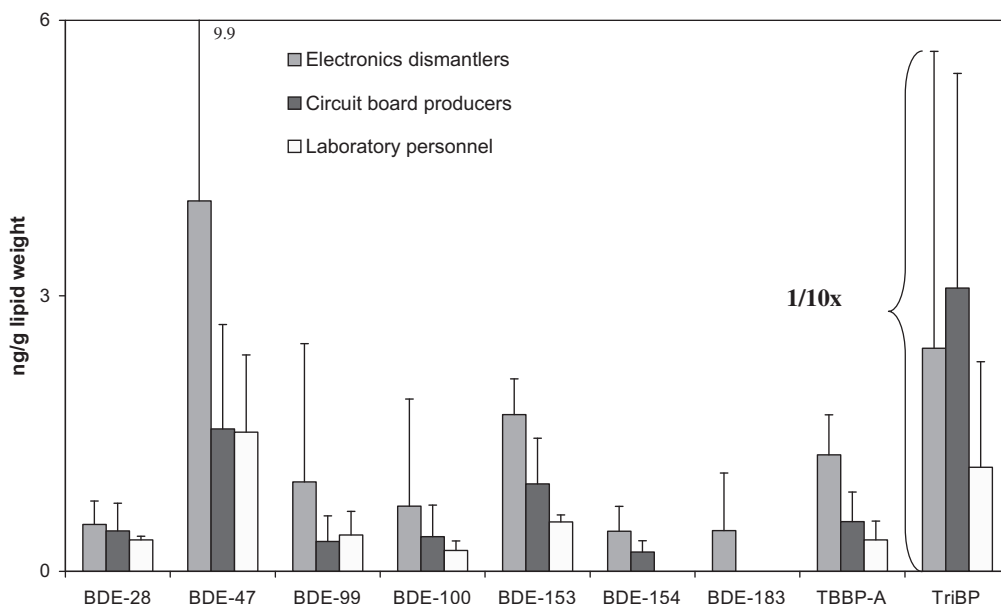


Fig. 3. The mean plasma concentrations in ng/g lipid weight of BFRs in the three occupational groups. The standard deviations are given as error bars. The mean concentrations and the standard deviation of TriBP have been divided by a factor of 10. Reproduced from Thomsen et al. (2001) by permission of The Royal Society of Chemistry.

3.1. Typical e-waste recycling methods

Recycling consists of the following major steps: (a) disassembly: selective disassembly, targeting and singling out hazardous or valuable components for special treatment; (b) upgrading: mechanical processing and/or metallurgical processing to upgrade the content of desirable materials; (c) refining: purifying the recovered materials using chemical (metallurgical) processing so as they are acceptable for the original use (Cui and Forsberg, 2003).

Disassembly is usually done manually and, at this stage, certain components (casings, external cables, CRTs, PCBs, batteries, etc.) are separated. Following disassembly, a wide range of methods used in the upgrading and refining stages of the recycling chain can be divided into mechanical and metallurgical methods depending on the nature of the processes employed.

Mechanical processes are usually employed during the upgrading stage, when the various metals and materials contained in e-waste are liberated and separated by some kind of shredding or crushing process. After size reduction, the materials are sorted into defined output fractions based on their specific physical characteristics, such as weight, size, shape, density, and electrical and magnetic characteristics. Typical sorting processes used are magnetic separation of ferrous parts, Eddy current separation (electric conductivity) of aluminium, and gravity separation (water or airflow tables, heavy media floating, sifting). Final output streams are usually components taken out as a whole, a magnetic fraction (going for further treatment to a steel plant), an aluminium fraction (to aluminium smelters), a copper fraction (to copper smelter), sometimes clean plastic fraction, and waste (Cui and Forsberg, 2003).

Metallurgical processes are used in the upgrading and refining stages of the recycling chain. In metallurgical processes, metals are melted (pyrometallurgical processes) or dissolved (hydrometallurgical processes) and further sorted by making use of their chemical/metallurgical properties. Pyrometallurgical processing, notably smelting, has become a traditional method to recover metals from e-waste in the last two decades (Cui and Zhang, 2008). In hydrometallurgical treatment, the main steps are acid or caustic leaching of solid material. From the solutions, the metals

of interest are then isolated and concentrated. Leaching solvents are mainly H_2SO_4 and H_2O_2 , *aqua regia*, thiourea, cyanide leach solutions, HNO_3 , NaOH , HCl , etc. (Antrekowitsch et al., 2006).

Overall, there are two types of facilities engaged in the recycling chain according to the nature of the methods involved. The first group is the facilities that are principally engaged in the dismantling and mechanical processing of e-waste for the recovery of raw materials. Fig. 1 demonstrates the process flow at a Japanese recycling facility belonging to this group. The second group is the facilities employing metallurgical processes to recover metals.

3.2. Hazards and risks associated with e-waste recycling

The degree of hazard posed to workers and the environment, thus, varies greatly depending on the specifics of the individual facility operations. For example, some manual disassembly operations pose few health or environmental risks, while others that involve the breaking of CRTs or the use of shredders present a range of more serious concerns.

The hazard associated with disassembly stage is the possibility of accidental releases and spillages of hazardous substances. For example, mercury, found within light sources (fluorescent tubes in scanners, photocopiers, etc.) as well as switches, could be released into the air of a recycling facility upon breakage of the shell (Aucott et al., 2003). CRTs present risk of implosion due to vacuum inside the tubes and inhalation hazard due to phosphor coating on the inner side of the CRT glass.

The primary hazards of mechanical treatment methods are associated with the size reduction and separation steps. Shredding, grinding or other size reduction processes generate dusts of the components being shredded in the facility. The composition of the dusts formed during this process includes plastics, metals, ceramic, and silica (glass and silicon dust) (MJC, 2004). Separation processes are associated with the same hazard of dust, as during the step shredded particles are handled. The dusts may pose an inhalation and dermal exposure hazard to workers as well as risk of environmental contamination.

There is scientific evidence that hazardous substances are released during shredding. In a US based electronics recycling facility, assessment of air quality in the vicinity of electronic waste shredders has shown cadmium and lead levels as high as 0.27 and $1.4 \mu\text{g}/\text{m}^3$, respectively (Peters-Michaud et al., 2003). The finding indicates that there was workplace contamination and a possibility of continuous exposure of workers to the toxic metals.

Shredding of plastics flame retarded with BFRs leads to the release of the chemicals into the ambient environment. There is a relatively large body of information regarding the fate of the chemicals during recycling processes.

BFRs, particularly PBDEs, were detected in the grams per kilogram concentration range in the fine dust fraction recovered in the off-gas purification system of a Swiss recycling plant engaged in mechanical treatment of e-waste (Morf et al., 2005). This emphasizes the high potential for BFR emissions during the mechanical processing of e-waste.

Tagigami et al. (2006) measured concentrations of BFRs, including PBDEs, TBBPA and hexabromocyclododecane (HBCD), and polybrominated dibenzo-*p*-dioxins/dibenzofurans (PBDDs/Fs) in the air of a TV recycling facility. All the chemicals were detected at concentrations higher than background levels. During the shredding process of TV housing cabinets, concentrations of the investigated brominated compounds were one to two orders of magnitude higher compared to the levels in the dismantling hall air.

Sjödin et al. (2001) reported concentrations of brominated and organophosphate flame retardants in the air at an electronics recycling facility and other environments (a factory assembling

PCBs, a computer repair facility, offices equipped with computers, and outdoor air). The highest concentrations of all compounds were detected in air from the recycling plant, with average concentrations of BDE-209, TBBPA and triphenyl phosphate (TPP) in air of the dismantling hall of the recycling plant equivalent to 38, 55 and $58 \text{ pmol}/\text{m}^3$, respectively. Significantly higher levels of these additives were present in air in the vicinity of a shredder at the dismantling plant. The lowest concentrations within the recycling plant were detected in a storage area, far away from the shredder.

The same research group assessed exposure of workers at the above recycling plant to PBDEs (Sjödin et al., 1999). Serum samples from 19 workers were analyzed for PBDEs and the results were compared with the serum PBDE levels of clerks working full-time at computer screens and hospital cleaners (control group). The total median PBDE concentrations in the serum from workers at the electronics-dismantling plant, clerks, and cleaners were 37, 7.3, and $5.4 \text{ pmol}/\text{g lw}$, respectively (Fig. 2). The results show that PBDEs are bioavailable and that occupational exposure to PBDEs occurs at the electronics-dismantling plant.

When the results from the air measurements at the electronics recycling plant (Sjödin et al., 2001) and serum concentrations of PBDEs in the workers (Sjödin et al., 1999) were reported, the company took measures to reduce the exposure of the dismantlers. The main contamination source, the shredder, was moved outside the dismantling hall, process ventilation system was upgraded. A follow-up study (Thuresson et al., 2006) revealed that the changes clearly reduced occupational exposure to BDE-183 and BDE-209 at the plant. Even though the amount of processed goods had doubled in 2000 as compared to 1997, there was a significant decrease in the serum levels of BDE-183 and BDE-209.

A research group from Norway (Thomsen et al., 2001) also investigated how exposure to BFRs is related to specific occupations, using plasma samples from three occupational groups: workers at an electronics dismantling facility, workers engaged in the production of PCBs and laboratory personnel. The subjects working at the electronics-dismantling plant had significantly higher plasma levels of TBBPA and BDE-153 compared to the other groups, and the hepta-brominated congener BDE-183 was only detected in plasma from this group (Fig. 3).

Pyrometallurgical processes, particularly smelting, are widely practiced for metal recovery from e-waste. Hazards associated with the pyrometallurgical processes are possible emissions of fumes of metals, particularly the low melting point metals like copper, cadmium, lead, etc.

Two studies were located in the scientific literature that investigated emissions of metals from smelting. Both the studies assessed metal emissions from a copper smelter of Noranda Inc. in Quebec, Canada (Telme et al., 2004; Zdanowicz et al., 2006). The smelter was processing metal scrap from e-waste as one of its feedstocks. Telme et al. (2004) monitored the levels of 35 different elements in snow up to a radius of 50 km around the smelter and found that many of the elements (Cu, Ag, In, Sb, Pb, As, Tl, Mo, Zn, Cd, Co, Be, Ni, Na, Ba, Fe, Cr, V, Ti, Y, Al, U, Ce, Li, S, La, and Sr) were emitted from the smelter. The concentrations of many of the metals remained higher than the regional background levels even at a distance of 50 km from the smelter. Concentrations of Cu, Pb, and Zn near the smelter were 525, 353, and $149 \mu\text{g}/\text{L}_{\text{meltwater}}^1$ as compared to the regional background concentrations of 1.1, 1.7, and $1.6 \mu\text{g}/\text{L}_{\text{meltwater}}$, respectively. Zdanowicz et al. (2006) analyzed the elemental composition of particulate matter in air and snow near the Noranda's copper smelter. Around 58% of particles in the smelter plume were metal-bearing particles, while in ambient air or snow

¹ Meltwater = melted snow.

around 15% were such particles. Pb was dominant in air-filtered particles, even those collected far (>60 km) from the smelter.

Pyrometallurgical treatment of e-waste also raises concerns regarding possible formation of brominated and chlorinated dibenzofurans and -dioxins in burning processes due to the presence of halogens in plastic parts of the e-waste feedstock (e.g., chlorine in PVC and bromine in BFR treated plastics). Numerous scientific studies have shown that thermal treatment of bromine and chlorine containing substances may lead to the formation of chlorinated, brominated and mixed chlorinated–brominated dibenzodioxins and -furans (PCDDs/Fs, PBDDs/Fs and PXDDs/Fs) (see review by Weber and Kuch, 2003).

Although the formation of PCDDs/Fs, PBDDs/Fs and PXDDs/Fs was observed in laboratory tests and studies on actual incineration, there are no scientific data on emissions of these substances specifically from pyrometallurgical treatment of e-waste. Some data are only available from personal communication of Allsopp et al. (2006) with staff of the integrated smelters in Belgium (Umicore) and Sweden (Boliden) who were dealing with the smelting of e-waste. Information from Umicore explained that chlorinated dioxin emissions were low (below the regulatory standards) due to destruction by high temperatures (1200–1300 °C), rapid cooling of the gases and a gas cleaning system. At the time of the survey (ca. 2006), brominated dioxins and furans were not routinely measured at Umicore and Boliden.

Although it seems possible to control dioxin emissions through the design of the technological process (high temperature, off-gas treatment, etc.), Hagelüken et al. (2006) raised concerns that not every smelter can currently process e-waste in an environmentally sound manner. According to Hagelüken et al. (2006), state-of-the-art integrated metal smelters designed for the treatment of electronic scrap have the necessary off-gas treatment systems and can safely prevent dioxin emissions; however standard copper smelters, designed for the treatment of mining concentrates or simple copper scrap, usually are lacking such installations.

Hydrometallurgical processes used to further upgrade and refine metals recovered by pyrometallurgical methods are associated with risks of exposure to acid fumes, acid in its liquid form, as well as cleaning solvents which may be used to prepare the shreds for acid etching (MJC, 2004).

Overall, the available data on environmental and occupational impacts of e-waste recycling in developed countries are fragmentary. There is a paucity of workplace monitoring data and virtually no studies on the effects of occupational exposure to e-waste-associated chemicals. E-waste recycling is an emerging, evolving industry and, perhaps therefore, its hazards appear to have been overlooked so far. Hard data on emissions of the chemicals of concern in the indoor environment at e-waste recycling facilities are required in order to support risk assessment and establish industry specific guidelines (e.g., permissible workplace levels, occupational exposure limits, etc.) which seem to be lacking at present. Such data would also be useful in designing the recycling processes to avoid/mitigate the occupational health risks. There is also a lack of studies assessing the impact of e-waste recycling on the outer environment. Monitoring of the environmental media outside the recycling facilities is thus needed in order to ascertain if there are any risks for the environment and the general public.

3.3. Hazards and risks associated with incineration of e-waste

Concerns over such treatment option are similar to those raised for pyrometallurgical treatment of e-waste, i.e., the possible formation of polyhalogenated dioxins and furans and emissions of metal fumes.

Stewart and Lemieux (2003) conducted experiments on incineration of a mixture of personal computer motherboards, keyboards

and cases using pilot-scale rotary kiln incinerator. The flue gas was analyzed for metals, halogens, volatile and semi-volatile organic products of incomplete combustion, including PCDDs/Fs. Measured metal emissions were significant, and consisted primarily of copper, lead, and antimony, while emissions of PCDDs/Fs were well below regulatory limits. Based on the results, Stewart and Lemieux (2003) suggested that incineration may be a viable option for electronics waste disposal, provided an appropriate particulate control device is used to control metal emissions.

The monitoring of halogenated dioxins and furans (PXDDs/Fs) from controlled combustion of BFR-containing waste was done in several other studies (Funcke and Hemminghaus, 1997; Vehlow et al., 2000; Sakai et al., 2001; Söderström and Marklund, 2002; Tange and Drohmann, 2005; Watanabe et al., 2008).

Söderström and Marklund (2002) combusted municipal solid waste pellets treated with three BFRs, decabromodiphenylether (Deca-BDE), HBCD, and TBPPA. All of the bromine–chlorine containing fuels formed PXDDs/Fs as well as PCDDs/Fs and PBDDs/Fs when burned in a reactor.

However, the association between content of BFRs in real e-waste and formation and/or release of dioxins and furans from its controlled combustion is less clear. Some studies indicate formation of dioxins and furans from combustion of e-waste and importance of bromine content in the feedstock (Funcke and Hemminghaus, 1997; Watanabe et al., 2008), others, to the contrary, show thermal destruction of the dioxins and furans and little effect of bromine/chlorine content on the final amounts of dioxins and furans (Vehlow et al., 2000; Sakai et al., 2001).

One study (Funcke and Hemminghaus, 1997) did observe the formation of PBDDs/Fs and PXDDs/Fs as a result of combustion of BFR-containing e-waste. The experiment involved combustion of municipal waste and co-combustion of municipal waste with e-waste. When BFR-containing e-waste was added, the quantity of PBDDs/Fs and PXDDs/Fs in the flue gas increased.

Watanabe et al. (2008) also observed the formation of PBDDs/Fs, PCDDs/Fs, and PXDDs/Fs during combustion of waste PCBs in a pilot-scale incinerator, but most of the formed brominated and chlorinated compounds were decomposed and/or removed during the flue gas treatment and, as a result, were not detected in flue gas at the final exit. Along with the formation of dioxins and furans, decomposition of BFRs, notably PBDEs, TBBPA and decabromodiphenylethane, was observed. The decomposition rates of these compounds were 30–99.999%.

Sakai et al. (2001) combusted used TV casings and waste PCBs under controlled conditions in a test incinerator equipped with a flue gas treatment system. The experiments demonstrated a high destruction efficiency of BFRs. PBDDs/Fs present in the input materials were also decomposed during the incineration process, i.e., input amount of total PXDDs/Fs were lower than output amount. The overall destruction rate in all runs was more than 90%.

In a series of incineration experiments (Vehlow et al., 2000; Tange and Drohmann, 2005), municipal solid waste containing up to 20% wt. of different types of e-waste plastics was combusted in a test incinerator. Although the elevated bromine concentrations resulted in increased proportion of mixed chlorinated–brominated dioxins and furans (PXDDs/Fs), the total levels of PXDDs/Fs were not altered significantly by the co-combustion of materials containing BFRs. Similar to the results of Sakai et al. (2001), more than 90% of PBDDs/Fs present in the input materials were destroyed in these combustion tests (Tange and Drohmann, 2005).

Regardless of their results, all of the studies did emphasize the importance of adequate flue gas treatment. For example, in the study by Watanabe et al. (2008) levels of dioxins and furans in flue gas dropped significantly after flue gas treatment (a difference in the levels in kiln exit gas and final exit gas was up to two orders of magnitude). This indicates that BFRs and the formed PXDDs/Fs

could be decomposed/removed under controlled combustion conditions with efficient flue gas treatment system.

3.4. Hazards and risks associated with landfilling of e-waste and waste residues from e-waste recycling

The hazards associated with placing e-waste in landfills are due to the variety of substances they contain. The main problem in this context is the leaching and evaporation of hazardous substances.

Townsend et al. (1999) assessed the leachability of thirty-six CRTs using Toxic Characteristic Leaching Procedure (TCLP). Twenty-one of the thirty color CRTs exceeded the 5 mg/l of lead regulatory limit for characterization as a hazardous waste. The largest concentration of leachable lead came from the funnel portion of the CRTs at an average lead concentration of 75.3 mg/L. Based on the results, the authors called for inclusion of CRTs into regulatory programs targeting hazardous chemicals.

In their another study, Townsend et al. (2004) tested 12 different types of electronic devices (CPUs, computer monitors, laptops, TV sets, printers, VCRs, cellular phones, remote controls, etc.). In many cases, lead concentrations in the leachates exceeded the regulatory limit of 5 mg/L and every device type leached lead above this level in at least one test. The authors concluded that the results provided sufficient evidence that discarded electronic devices that contain a color CRT or printer wiring boards with lead-bearing solder have a potential to be hazardous wastes for lead.

Osako et al. (2004) showed the presence of BFRs in leachate from landfills in Japan. Higher concentrations of BFRs (PBDEs and TBBPA) were detected in the landfills that had crushed e-waste.

Besides the leaching of substances in landfills, there is also a risk of vaporization of volatile hazardous substances. For example, for mercury, both the leaching and vaporization of metallic mercury and methylated mercury are of concern. Dimethyl mercury, an organic form of mercury, was detected in landfill gas at levels 1000 times higher than what has been measured in open air (Lindberg et al., 2001).

4. Hazards and risks associated with e-waste treatment in developing countries

E-waste recycling sector in developing countries is largely unregulated, and e-waste is often processed to recover valuable materials in small workshops using rudimentary recycling methods. In addition to domestically generated e-waste, developing countries with lax environmental legislation and cheap labor are often the destinations for e-waste generated abroad. China, India and Pakistan have been identified as common destinations for e-waste in Asia (BAN & SVTC, 2002; Brigden et al., 2005). Recently, there has been an increase in e-waste recycling activities in other regions, particularly in some African countries, including Ghana (Brigden et al., 2008).

E-waste recycling operations in several locations in China, India and Ghana have been particularly well investigated. The locations in India, Pakistan and Ghana are New Delhi, Karachi and Accra, respectively (BAN & SVTC, 2002; Brigden et al., 2005, 2008). The most prominent areas for the informal processing of e-waste in China are in southern Guangdong Province and around the city of Taizhou, in eastern Zhejiang Province (Hicks et al., 2005). The town of Guiyu, in Guangdong Province, has attracted a lot of attention from NGOs and scientists (BAN & SVTC, 2002; Brigden et al., 2005; and a number of publications reviewed below). It is, in a sense, an established e-waste recycling center with the recycling activities being a fundamental part of Guiyu's economy (Hicks et al., 2005).

4.1. Methods employed for recovery of valuable materials

In Ghana, the primary activities were the manual disassembly of e-waste to isolate metals (mainly copper and aluminium) and the open burning of certain components to isolate copper from plastics in which they are encased, particularly from plastic coated wires and cables (Brigden et al., 2008). In India and China, where more complex processes are employed (Fig. 4), the recycling practices include manual disassembly of e-waste with little regard to its hazardous content (for example, breaking CRTs to remove

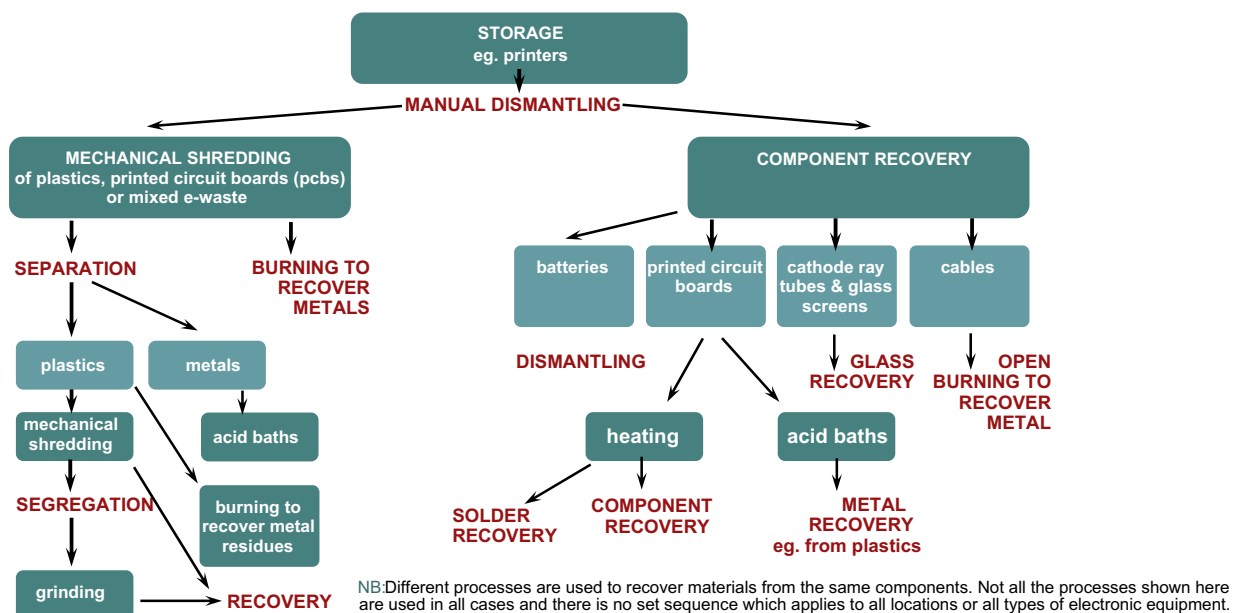


Fig. 4. WEEE recycling processes in India and China. Reproduced from Brigden et al. (2005) with permission from Greenpeace International.

yokes), recovery of solder and chips from PCBs by heating the boards, acid extraction of metals from complex mixtures, melting and extruding plastics, and burning of plastics to isolate metals (BAN & SVTC, 2002; Brigden et al., 2005).

In the manual disassembly process, CRTs are broken to remove copper yokes that are further used for copper recovery. This exposes the worker to the phosphor powder covering the inner surface of the front panel. Environmental pollution is also a likely outcome of the breaking and further handling of CRTs. In Guiyu, broken CRTs were dumped on open land after removal of the yokes (BAN & SVTC, 2002). In India, CRTs were reportedly smelted for recovery of glass, but prior to the treatment they were stored in an open area (Brigden et al., 2005). The open air storage and dumping of CRTs raise concerns regarding the possibility of lead contained in the CRT glass leaching out into the environment.

To recover valuables and solder from PCBs, the boards are heated until the connecting solder is melted. Heating is done using coal grills, propane torches, kerosene burners, or other simple devices. Melted solder is then collected and individual components attached to PCBs are manually removed. Valuable chips are sold or subject to acid digestion for precious metal extraction. Waste boards stripped of chips are further burnt or acid digested in order to recover the remaining metals. Heating of PCBs for de-soldering and removal of chips undoubtedly exposes the worker to fumes of metals, particularly those in solder (often lead and tin), and other hazardous substances that can be potentially released during such treatment.

In both China and India, primitive hydrometallurgical processes are used to recover metals from e-waste (BAN & SVTC, 2002; Brigden et al., 2005). Metals are dissolved in strong acid solutions and subsequently recovered from the solutions. According to Brigden et al. (2005) in Guiyu, China, the workshops were situated in the open on the banks of rivers, while in Delhi, India, this type of activity took place in small, enclosed workshops. Mixtures of concentrated nitric acid and hydrochloric acids were reportedly used in Guiyu (BAN & SVTC, 2002) and Delhi (Brigden et al., 2005) for the extraction of gold and copper, respectively. Various volatile compounds of nitrogen and chlorine are known to be emitted during such processes. The wastes generated along the process, i.e., waste acid solutions and sludges, were poured out and dumped onto open ground or into water streams.

Plastics are processed in a similar way in both China and India (Brigden et al., 2005). It is manually removed from e-waste and mechanically shredded. The next treatment step may be some kind of separation (e.g., by color or density) and/or further grinding. Plastics melting and extruding operations were reported to be taking place in Guiyu (Brigden et al., 2005; BAN & SVTC, 2002).

E-waste parts are burned on open fires to recover metals from plastics in which they are encased; this includes plastic coated wires as well as other complex components (Brigden et al., 2005, 2008). Open burning of unwanted scrap and wastes is also a common practice everywhere. Due to the presence of PVC and BFRs in plastics, such burning would likely result in formation of PXDDs/Fs. The formation of PXDDs/Fs was observed in experimental studies on simulating open burning of wires and PCBs (Leung et al., 2006; Gullet et al., 2007). In both the studies, exceptionally high emissions of PCDDs/Fs were observed during open burning of insulated wire, about three orders of magnitude higher than those for the open burning of household waste.

4.2. Workplace and environmental contamination

Rudimentary recycling techniques coupled with the amounts of e-waste processed have already resulted in adverse environmental and human health impacts in China, India and Ghana (Brigden et al. (2005, 2008) and a number of publications reviewed below).

In contrast to the situation in developed countries, the environmental and human health impacts of e-waste recycling in developing countries are relatively well documented, particularly for Guiyu in China, while there is less information for India and Ghana (except for the reports by Brigden et al. (2005, 2008)). A review article by Sepùlveda et al. (2010) assessed the magnitude of environmental contamination at e-waste recycling sites in China and India by comparing the data with known concentration thresholds and other pollution level standards. The review highlighted very high levels of lead, PBDEs, PCDDs/Fs and PBDDs/Fs in air, bottom ash, dust, soil, water and sediments in e-waste recycling areas of the two countries suggesting a serious threat to the environment and human health. The concentration levels found sometimes exceeded the reference values for the sites under investigation and pollution observed in other industrial or urban areas by several orders of magnitude.

4.2.1. Dust

Brigden et al. (2005) screened dust samples from the workshops in China and India involved in de-soldering and PCB disassembly. With the exception of one sample, all other samples from contained extremely high concentrations of lead and tin. For all dusts collected from the workshops in China, the concentrations of lead (31,300–76,000 mg/kg) were hundreds of times higher than typical levels in indoor dusts. The levels of lead in Indian workshop dusts (2360–10,900 mg/kg) were elevated by approximately 5–20 times background levels. Tin concentrations in the same samples were in the range 25,100–293,000 mg/kg and 3140–17,400 mg/kg for China and India, respectively. For all samples from both countries, high lead concentrations were associated with high tin concentrations, indicating a common source. Other metals found at elevated concentrations in the dust samples from the workshops in both China and India were antimony, cadmium, copper, nickel, silver and zinc.

Leung et al. (2008) evaluated the extent of heavy metals (Cd, Co, Cr, Cu, Ni, Pb, Zn) contamination from PCB recycling in Guiyu using surface dust samples collected from recycling workshops, adjacent roads, a schoolyard, and an outdoor food market. Elevated concentrations of lead, copper, zinc and nickel were detected in workshop dust (with mean values of 110,000, 8360, 4420, and 1500 mg/kg, respectively) and in dust from adjacent roads (22,600, 6170, 2370, and 304 mg/kg, respectively). In road dust, lead and copper levels were 330 and 106 mg/kg, which were 371 and 155 times higher, respectively, than in non-e-waste areas located 8 and 30 km away. Levels at the schoolyard and food market showed that public places were adversely affected.

4.2.2. Air

Elevated concentrations of metals were also observed in ambient air in Guiyu (Deng et al., 2006). Cd, Cr, Cu, Ni, Pb, Zn, Mn and As were monitored in 29 air samples of total suspended particles (TSP, particles less than 30–60 μm) and 30 samples of particles with aerodynamic diameter smaller than 2.5 μm (PM_{2.5}). In both the TSP and PM_{2.5} fractions, the most enriched metals were chromium (with mean levels of 1161 and 1152 ng/m³, respectively), zinc (1038 and 924 ng/m³), lead (444 and 392 ng/m³), manganese (60.6 and 25.42 ng/m³) and copper (483 and 126 ng/m³). Concentrations of most of the metals in the ambient air in Guiyu were much higher than those observed for other sites in Asia. Concentrations of chromium, copper and zinc in PM_{2.5} were 4–33 times higher than in the Asian metropolitan cities such as Tokyo, Shanghai, Ho Chi Minh, Taichung and Seoul. The same ambient air samples were also screened in this study for 16 US EPA priority polycyclic aromatic hydrocarbons (PAHs). Elevated concentrations of benzo(a)pyrene, a well known carcinogen, were of concern. The

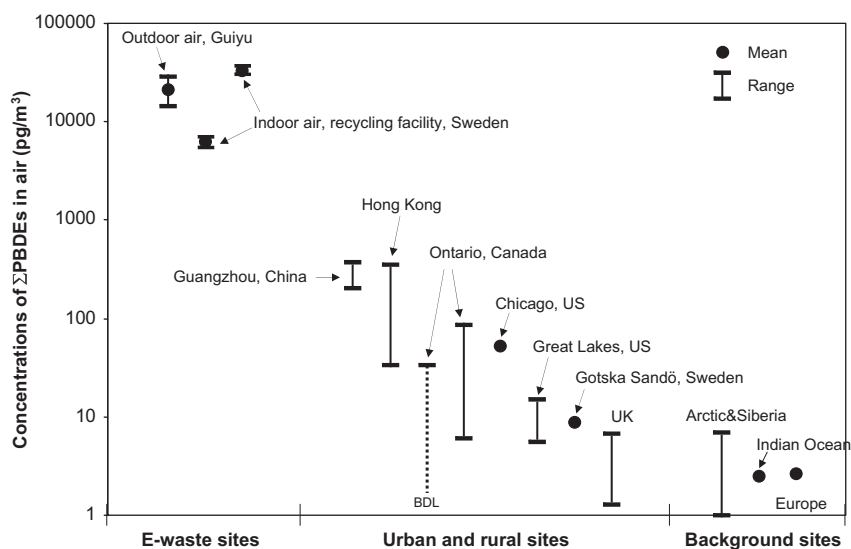


Fig. 5. Comparison of PBDE concentrations in air particles in Guiyu and other sites. Based on the data compiled by Deng et al. (2007). BDL = below detection limit.

average concentration of benzo(a)pyrene was 2–6 times higher than in other Asian cities.

In another study, the same research group (Deng et al., 2007) monitored PBDE concentrations in TSP and PM_{2.5} fractions of ambient air in Guiyu. In addition, air samples from three urban sites in Hong Kong and two urban sites in Guangzhou were also examined. The monthly concentrations of the sum of 22 BDE congeners contained in TSP and PM_{2.5} at Guiyu were 21.5 and 16.6 ng/m³, up to 58–691 times higher than the levels for other urban sites and more than 100 times higher than concentrations reported for other locations (Fig. 5).

Similar to metals, PAHs, and PBDEs, PCDDs/Fs and PBDDs/Fs were also detected at high concentrations in ambient air in Guiyu (Li et al., 2007). Atmospheric PCDD/F (tetra to octa) concentrations and toxic equivalent (TEQ) values were 64.9–2365 pg/m³ and 0.909–48.9 pg of W-TEQ/m³, respectively; the highest documented levels of these compounds in ambient air in the world. PBDDs/Fs (eight 2,3,7,8-substituted congeners) were also found at high levels (concentrations of 8.124–61 pg/m³ and 1.6–2104 pg of I-TEQ/m³). Profiles of the 2,3,7,8-PCDD/F homologues in the air of Guiyu differed from typical urban air patterns reported in the literature, and the concentration of homologues increased with the chlorination degree of 2,3,7,8-PCDDs/Fs except for OCDF. The severe dioxin pollution present in Guiyu was found to spread to the adjacent area of Chendian, where atmospheric PCDD/F and 2,3,7,8-PBDD/F levels were higher than those commonly observed in urban areas of the world. Inhalation risk assessment showed that residents in Guiyu are at a high risk of exposure to dioxins. The total PCDD/F intake doses far exceeded the WHO 1998 tolerable daily intake limit of 1–4 pg of W-TEQ/kg/day.

4.2.3. Freshwater

Freshwater ecosystems in Guiyu have also been affected by the intensive recycling activities taking place there. Freshwater analysis of dissolved metals showed that the metal concentrations were higher in water of Lianjiang and Nanyang rivers within Guiyu than in a reservoir outside of Guiyu (Wong et al., 2007a). Lianjiang was enriched with dissolved As, Cr, Li, Mo, Sb and Se, while Nanyang river had elevated dissolved Ag, Be, Cd, Co, Cu, Ni, Pb and Zn. Excessive levels of the metals were attributed by the authors to acid leaching operations taking place along the rivers. Concentrations of metals varied during daytime (8 samples were collected during a day) suggesting recent discharges of metals. Analysis of

Pb isotopic composition confirmed that there was input of non-indigenous Pb isotopes into the rivers.

4.2.4. Soil and sediments

Leung et al. (2007) assessed levels of PBDEs and PCDDs/Fs in surface soils and combusted residue samples in Guiyu. Total PBDE concentrations were highest in combusted residue of plastic chips and cables collected from a residential area (33,000–97,400 ng/g, dry weight), in soils from an acid leaching site (2720–4250 ng/g, dry weight) and a printer roller dump site (593–2890 ng/g, dry weight). BDE-209 was the most dominant congener (35–82%) among the study sites indicating the prevalence of commercial Deca-BDE, however signature congeners from commercial Penta- and Octa-BDE were also found. PCDD/F concentrations were also highest in soil from the acid leaching site (12,500–89,800 pg/g, 203–1100 pg WHO-TEQ/g, dry weight) and in combusted residue (13,500–25,300 pg/g, 84.3–174 pg WHO-TEQ/g, dry weight) and were comparable to PCDD/F levels reported for some open dumping sites in Asian developing countries. Of the e-waste processing activities, acid leaching and open burning apparently emitted the highest concentrations of PBDEs and PCDDs/Fs.

Yu et al. (2006) measured sixteen US EPA priority PAHs in 49 soil samples from Guiyu. Total concentrations were the highest in soil from open burning sites (2065 µg/kg), followed by areas near burning sites (851 µg/kg), rice fields (354 µg/kg) and reservoir areas (125 µg/kg). The dominant PAHs were naphthalene, phenanthrene and fluoranthene, which are mainly derived from incomplete combustion of e-waste (e.g., wire insulations and PVC materials), and partly from coal combustion and motorcycle exhausts.

Leung et al. (2006) have analyzed PBDEs and metals in just three samples, but the samples were collected from places that were likely to be highly contaminated. Two soil samples were collected from a burnt plastic dump site and from a printer roller dump site, and a sediment sample was collected from Lianjiang River where e-waste was dumped. The total mono- to hepta-brominated substituted PBDE concentrations in the soils were 1140 and 1169 µg/kg dry wt., and were higher than the concentration in the sediment sample (32.3 µg/kg). The PBDE concentrations in soils from dumping sites were approximately 10–60 times those reported for other PBDE contaminated locations in the world. Among the metals analyzed, Cu, Pb, and Zn were the most abundant in the samples. Cu concentration in the soil from the printer

roller dump site (712 mg/kg) and the burnt plastic dump site (496 mg/kg), and sediments from Lianjiang River (528 mg/kg) exceeded the new Dutch list action value of 190 mg/kg (the Dutch guidelines were used for comparison since no such guidelines exist in China). No other metals exceeded the Dutch action level, however, Cd, Cu, Ni, Pb, and Zn concentrations in the three samples exceeded so called optimum values set by the same Dutch guidelines. In general, Cu, Pb, and Ni concentrations in the sediment sample of the Lianjiang River were higher than those measured in river and coastal sediments in Guangzhou, Deep Bay, Shenzhen, and Hong Kong.

Sediments of Linjiang and Nanyang rivers flowing through Guiyu were tested for metals by Wong et al. (2007b). Elevated concentrations of Cd (n.d. –10.3 mg/kg), Cu (17.0–4540 mg/kg), Ni (12.4–543 mg/kg), Pb (28.6–590 mg/kg), and Zn (51.3–324 mg/kg) were observed. The magnitude of contamination was higher in sediments of Lianjiang River than Nanyang River. The distribution of Cu, Pb and Zn concentrations of the Lianjiang sediments indicated that these metals were possibly discharged into the river simultaneously at various points. Pb isotopic composition in sediments indicated input of non-indigenous Pb isotopes into the rivers, higher in the case of Lianjiang.

4.3. Human exposure and health effects

As revealed by the studies reviewed in the previous section, unregulated recycling activities generate workplace and environmental contamination by a wide range of chemicals. As a result, the workers and local residents are exposed to the chemicals through inhalation, dust ingestion, dermal exposure, and dietary intake.

Inhalation and dust ingestion were suggested as particularly important routes of human exposure. An assessment of risk from dust ingestion conducted by Leung et al. (2008), revealed that ingestion of lead and copper contaminated dust may pose serious health risks to workers and local residents of Guiyu. For a PCB recycling worker, the estimated oral average daily dose of lead exceeded the “safe” oral reference dose for lead by 50 times, indicating a high risk of adverse health effects. The inhalation risk assessment conducted by Li et al. (2007) based on PCDD/F concentrations in ambient air showed that residents in Guiyu are at a high risk of exposure to dioxins too.

4.3.1. Occupational exposure

High exposure to PBDEs in Guiyu residents engaged in e-waste recycling was demonstrated by Bi et al. (2007). Concentrations of PBDEs, polychlorinated biphenyls, and organochlorine pesticides were measured in serum from residents of Guiyu ($n = 26$) and compared to a matching cohort ($n = 21$) from a nearby region where the fishing industry dominates (Haojiang). Serum concentrations of PBDEs and pesticides, but not polychlorinated biphenyls, were significantly different in the two regions: the median PBDE concentration was 3 times higher in Guiyu than Haojiang, whereas the opposite was true for pesticide dichlorodiphenyltrichloroethane. PBDEs typically accounted for 46% of the total organohalogen chemicals in samples from Guiyu, but 8.7% in Haojiang. The median BDE-209 concentration in Guiyu was 50–200 times higher than those previously reported in occupationally exposed populations. The highest BDE-209 concentration was 3100 ng/g lipid, the highest ever reported in humans.

In another study, Yuan et al. (2008) revealed that occupational exposure to PBDEs may have an effect on the levels of thyroid-stimulating hormone and cause genotoxic damage in e-waste recycling workers. In the study, 23 subjects were recruited among the workers of the e-waste recycling site (exposed group) and 26 subjects were selected from a community located 50 km away

from the recycling site (control group). Serum levels of PBDEs (median, 382 ng/g lipid weight; range, 77–8452 ng/g lipid weight) and thyroid-stimulating hormone (median, 1.79 μ IU/mL; range, 0.38–9.03 μ IU/mL) and frequencies of micronucleated binucleated cells (median, 5‰; range, 0–96‰) were significantly higher in the exposed group than in the control group (158 ng/g, range of 18–436 ng/g, and $p < 0.05$; 1.15 μ IU/mL, range of 0.48–2.09, and $p < 0.01$; and 0‰, range of 0–5‰, and $p < 0.01$, respectively).

Oxidative stress indicated by the elevated urinary 8-hydroxy-2'-deoxyguanosine levels was demonstrated in another group of exposed workers by Wen et al. (2008). The study evaluated levels of PCDDs/Fs, PBDEs, and polychlorinated biphenyls in hair samples from male workers ($n = 64$) and assessed levels of 8-hydroxy-2'-deoxyguanosine in their pre- and postworkshift urines (64 of each). The concentrations of PCDDs/Fs, PBDEs and polychlorinated biphenyls were the highest so far reported, e.g., PCDDs/Fs levels in the study were about 20 times higher than the upper limit of the concentration in healthy subjects in Japan, and polychlorinated biphenyls levels were nearly 2 orders of magnitude greater than those in hair samples from Japan and Belgium. The 8-hydroxy-2'-deoxyguanosine levels significantly increased from $6.40 \pm 1.64 \mu\text{mol/mol}$ creatinine in preworkshift urine to $24.55 \pm 5.96 \mu\text{mol/mol}$ creatinine in postworkshift urine ($p < 0.05$). The authors concluded that there was a high cancer risk due to oxidative stress indicated by the elevated 8-hydroxy-2'-deoxyguanosine levels in e-waste recycling workers exposed to high concentrations of PCDDs/Fs, PBDEs, and polychlorinated biphenyls.

4.3.2. General population exposure

The general population exposure to e-waste derived chemicals is best studied in Guiyu, where the population seem to be affected by the recycling activities. Residents of Guiyu have reported their children suffering from medical problems such as breathing ailments, skin infections, and stomach diseases. There has also been a surge in cases of leukemia (Leung et al., 2006). Drinking water has been contaminated and is transported from a town located 30 km away (BAN & SVTC, 2002).

The primitive e-waste recycling activities in Guiyu were apparently contributing to the elevated blood levels of lead (Pb) and cadmium (Cd) in children living there (Huo et al., 2007; Zheng et al., 2008).

Huo et al. (2007) found that blood lead levels in 165 children of Guiyu ranged from 4.40 to 32.67 $\mu\text{g/dL}$ with a mean of 15.3 $\mu\text{g/dL}$, whereas blood lead levels in 61 children of neighboring town Chendian (control site) were from 4.09 to 23.10 $\mu\text{g/dL}$ with a mean of 9.94 $\mu\text{g/dL}$. Of children in Guiyu, 81.8% had blood lead levels $> 10 \mu\text{g/dL}$, compared with 37.7% of children in Chendian ($p < 0.01$).

In a similar epidemiological survey (Zheng et al., 2008), 278 children under 8 years old from Guiyu and Chendian were tested for lead and cadmium in their blood. Similar to the previous

Table 2
Chromium levels in umbilical cord blood ($\mu\text{g/L}$) of newborn children in Guiyu compared with control group. Reproduced from Li et al. (2008) with permission from Elsevier.

Year	Group	N	Range	$X \pm s$	Median
2006	Guiyu	100	0.45–6029.92	306.20 ± 845.78	93.87 ^{a,b}
	Control	52	1.66–56.54	19.95 ± 8.37	18.10
2007	Guiyu	100	20.16–630.00	99.90 ± 96.77	70.60 ^c
	Control	50	8.62–197.18	32.48 ± 32.74	24.00

^a Compared with control group in the same year: $Z = -8.44$, $p < 0.01$.

^b Compared with control group in the same year: $Z = -8.08$, $p < 0.01$.

^c Compared between the year of 2006 and 2007 in Guiyu group: $Z = -0.999$, $p > 0.05$.

Table 3

Comparison of the typical e-waste management scenarios and associated hazards in developed and developing countries.

	Developed countries	Developing countries ^a
Typical recycling and waste disposal processes	Manual dismantling Semi-automatic separation Recovery of metals by state-of-the art methods in smelters and refineries Incineration with MSW ^b Landfill disposal	Manual dismantling Manual separation Recovery of metals by heating, burning and acid leaching of e-waste scrap in small workshops Open burning Open dumping
Occupational exposure hazard	Not well documented, apparently low Concentrations of Σ PBDEs in blood of electronics dismantlers: 15–75 ng/g lw ^c (Sweden; Sjödin et al., 1999) 3.8–24 ng/g lw (Norway; Thomsen et al., 2001)	High Levels of Σ PBDEs in blood of informal e-waste workers: 140–8500 ng/g lw (Guiyu, China; Bi et al., 2007) 77–8452 ng/g lw (China; Yuan et al., 2008)
Workplace contamination hazard	Not well documented, apparently low Indoor air concentrations of Σ PBDEs at recycling facilities: 510 ng/m ³ (TV recycling plant, Japan; Takigami et al., 2006) 96; 98; 260; 310 ng/m ³ (four measurements near a shredder at an electronics recycling plant, Sweden; Sjödin et al., 2001)	High Outdoor air concentrations of Σ PBDEs in Guiyu town, China: 21.5 ± 7.2 ng/m ³ (Deng et al., 2007)
Environmental contamination hazard	Not well documented	High

^a Informal recycling scenario was considered as “typical” in the case of developing countries.

^b MSW = municipal solid waste.

^c lw = lipid weight.

NB: No data on air concentrations in e-waste processing workshops were available for the comparison. However, the high outdoor concentrations are indicative of still higher concentrations in the e-waste workers' immediate environment

survey, children living in Guiyu had significantly higher blood levels of lead and cadmium as compared with those living in Chendian ($p < 0.01$). In Guiyu, 70.8% of children had blood lead levels $< 10 \mu\text{g/dL}$, and 20.1% of children had blood cadmium levels $> 2 \mu\text{g/L}$, compared with 38.7% and 7.3% of children, respectively, with such levels in Chendian ($p < 0.01$). A significant increasing trend in blood lead levels with increasing age was also observed in Guiyu ($p < 0.01$). The risk factors related to children's blood levels of lead and cadmium mainly included father's engagement in the work related to e-waste, children's residence in Guiyu and the amount of time that children played everyday outside.

In another epidemiological study involving neonates in Guiyu (in 2006, $n = 100$; in 2007, $n = 100$) and a control group of neonates from a fishing town of Chaonan (in 2006, $n = 52$; in 2007, $n = 50$), chromium levels of umbilical cord blood were measured and DNA damage of cord blood lymphocyte was assessed (Li et al., 2008). The mean chromium levels in umbilical cord blood of neonates in the Guiyu group in 2006 and 2007 were 303.38 and 99.90 $\mu\text{g/L}$, respectively, and were significantly higher than the results for the control group ($p < 0.01$) (Table 2). Higher levels of chromium in neonates were found to correlate with their mothers' exposure to e-waste recycling. There were significant differences in terms of DNA damage between the Guiyu group and the control group ($p < 0.05$). The authors attributed the DNA damage to high chromium levels in umbilical cord blood, based on the fact that there was a correlation between the two parameters ($p < 0.05$). However, the observed DNA damage might be due to different factors or a combination of factors. Nevertheless, the high Cr levels in umbilical cord blood of neonates are of concern and, probably, reflect the general environmental situation in Guiyu.

5. Comparison of e-waste management and related policy approaches in developed and developing countries

As shown above, the situation with regard to e-waste management is quite different in developed and developing countries. The informal e-waste recycling prevalent in developing countries is associated with severe environmental pollution and occupational exposure to the e-waste-derived chemicals. The situation is often

aggravated by a lack of relevant legislation and/or lax enforcement of the existing regulations. The e-waste recycling practices in developed countries are apparently less hazardous, although the available data are fragmentary. Table 3 summarizes the differences in the e-waste recycling scenarios and associated hazards. The differences between the typical developing and developed country scenarios are due to the differences in the socio-economic and legal contexts. While e-waste recycling in developing countries is largely uncontrolled and purely market-driven, in developed countries it is organized and based on the principle of Extended Producer Responsibility (EPR).

It is beyond the scope of this review paper to provide a comprehensive overview of the existing legislations in this field or to do justice to the large number of other relevant initiatives. However, the authors believe that it is useful to describe in general terms the current status of national and international policies developed to meet the challenges of e-waste.

5.1. Developed countries

Most of the OECD member countries, and some other nations, have developed legislations for e-waste based on the EPR principle. These policy initiatives shift the financial burden for e-waste collection and recycling from the public sector to the producers. In most cases they have been effective in establishing an adequate infrastructure for collection and treatment, and high shares of the discarded items are diverted from landfills and incinerators to recycling facilities (Bengtsson et al., 2009).

A complementary policy initiative, which has had profound impact on the global electronics industry, is the so-called RoHS Directive of the European Union.² This regulation practically bans the use of 6 substances (Pb, Hg, Cd, Cr⁶⁺, PBB and PBDE) in most kinds of electronic products. The RoHS Directive created a new more or less global standard on hazardous substances in electronics, but

² DIRECTIVE 2002/95/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment.

many producers are currently going beyond these requirements by phasing out also other substances of concern.

5.2. International trade

A special problem related with e-waste is the international trade from OECD countries to the developing world. The high treatment costs in the exporting countries, in combination with low labor costs and lax (or weakly enforced) environmental protection standards in developing countries create strong economic drivers for this trade. The ongoing relocation of industrial production from the OECD to the rest of the world, and the associated increasing demand for raw materials in rapidly industrializing countries, provides additional drivers for the e-waste trade (e.g., Hotta et al., 2008). International trade in second-hand electronic equipment adds further to this problematique; while such trade can contribute to bridging the “digital divide” to some extent, it also significantly increases the amount of e-waste in countries that seriously lack appropriate treatment capacity.

The most comprehensive international agreement to deal with the transboundary movements of hazardous waste is the Basel Convention,³ which entered into force in 1992. One of the key mechanisms of this agreement is a requirement for exporting countries to receive explicit permits from the countries of destination. This should in theory protect non-OECD countries from receiving unwanted shipments of hazardous waste. However, in practice, there are a number of factors that undermine the effectiveness of the Basel Convention in dealing with the e-waste issues. Firstly, one major country generating large volumes of e-waste – the USA – has not yet ratified the agreement.⁴ Secondly, the convention lists criteria for hazardous substances but fails to define limit-values for those substances. This will in some cases make it ambiguous whether a certain waste shipment should be categorized as hazardous or not. Thirdly, the difficulties to practically distinguish between second-hand items (which are not covered by the convention) and e-waste complicates the implementation. Fourthly, illegal waste shipments, made easier by insufficient capacity for border controls and lax enforcement, are still common.

5.3. Developing countries

As indicated above, import of e-waste is causing environmental and health problems in a number of developing countries. The policies developed so far center mainly on banning inappropriate practices, such as open burning, and on regulating imports. However, the enforcement of such policies has so far been relatively weak and only marginally managed to deal with the risks of e-waste treatment. In addition, most of these countries also generate increasing volumes of domestic e-waste that needs to be treated (e.g., Yu et al., 2010). Even though all transboundary waste shipments to developing countries could be stopped, these countries would still be facing growing problems and a need to rapidly build appropriate capacity. The authors believe that it is an urgent task, not only for these countries, but for the international community to develop appropriate responses to this challenge.

6. Conclusions

The reviewed studies collectively reveal that e-waste contains a number of hazardous substances. Heavy metals and halogenated compounds are of particular concern. Hazardous substances are

often concentrated in certain e-waste components/parts. Thus, improper handling and management of e-waste during recycling and other end-of-life treatment options may pose potentially significant risks to both human health and the environment.

Although there is a paucity of scientific evidence on environmental and occupational impacts of e-waste recycling in developed countries, the available fragmentary data suggest that the major hazards during e-waste recycling are associated with the size reduction and separation and pyrometallurgical treatment steps. Shredding leads to the formation of dust composed of plastics, metals, ceramic, and silica (glass and silicon dust). Additive chemicals like BFRs which are embedded in electrical and electronic equipment are also released during shredding. Pyrometallurgical treatment generates fumes of heavy metals (especially low melting point metals such as Hg, Pb, Cd, etc.). Besides, if the feedstock contained PVC or other plastics flame retarded with BFRs (PBDEs, TBBPA, PBBs, HBCDs, etc.), pyrometallurgical treatment may lead to the formation of mixed halogenated dioxins and furans (PXDD/Fs, where X = Cl, Br).

More data on emissions of the chemicals of concern in the indoor environment at e-waste recycling facilities are required in order to support risk assessment and establish industry specific guidelines (e.g., permissible workplace levels, occupational exposure limits, etc.) which seem to be lacking at present. Exposure to substances of concern can occur throughout the e-waste processing cycle via inhalation or dermal exposure pathways. However, there is a lack of information on occupational exposure during e-waste recycling in industrialized/developed countries. The data are only available for three groups of electronics dismantling workers whose blood samples were analyzed for BFRs. The results demonstrated that the electronics dismantling workers had been exposed to higher levels of BFRs than general population as a result of processing BFR treated plastics.

Other end-of-life treatment options for e-waste, i.e., incineration and landfilling, are also associated with potential risks such as formation of polyhalogenated dioxins and furans and emissions of metal fumes during incineration of e-waste and leaching and evaporation of various hazardous substances in landfills.

E-waste recycling operations in developing countries are mostly unregulated and employ rudimentary techniques. The potentially hazardous recycling practices include manual disassembly of e-waste with little regard to its hazardous content, recovery of solder and chips from PCBs by heating them, acid extraction of metals from complex mixtures, melting and extruding plastics, and burning of plastics to isolate metals. The crude recycling of e-waste practiced in developing countries leads to significant releases of various chemicals into the environment. This is substantiated by the high levels of various chemicals observed in the workplace and ambient environment in e-waste recycling areas. The chemicals commonly detected at elevated levels in the environment were those incorporated into e-waste (e.g., metals, PBDEs) or generated through processing of e-waste (PXDDs/Fs). The exposure of workers and the general population to e-waste-derived hazardous chemicals may be significant. Higher levels of various chemicals were observed in e-waste recycling workers and people residing close to the recycling sites than in control groups of people living far away from such sites. The high levels of some chemicals were associated with changes in clinical parameters in exposed groups, indicating induction of toxic effects.

Overall, there is a paucity of empirical data on which to base the assessment of environmental and human health risks of various e-waste treatment options. While potential hazards of e-waste itself, i.e., its hazardous content, are relatively well known, there are only fragmentary data concerning actual releases of hazardous chemicals and human health effects due to e-waste treatment processes. The lack of data greatly limits objective assessment

³ The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal.

⁴ As of March 2010.

and management of the existing risks. Given the paucity of scientific evidence, further research should be done to ascertain the potential risks. However, there is enough knowledge to distinguish between safer and riskier treatment practices. There is no doubt that the simple recycling carried out in many developing countries is causing risks that could to a large extent be avoided through the use of improved treatment methods.

List of abbreviations

Components/parts of electronic and electrical equipment

CRTs	cathode ray tubes
LCDs	liquid crystal displays
PCBs	printed circuit boards
PVC	polyvinylchloride; plastic used in wire coating, insulation and other applications

Flame retardants

HBCDs	hexabromocyclododecanes
PBDEs	polybrominated diphenyl ethers
TBBPA	tetrabromobisphenol-A
TPP	triphenyl phosphite

By-products of e-waste treatment processes

PAHs	polycyclic aromatic hydrocarbons
PBDDs/Fs	brominated dibenzo- <i>p</i> -dioxins and furans
PCDDs/Fs	polychlorinated dibenzo- <i>p</i> -dioxins and furans
PXDDs/Fs	mixed chlorinated-brominated dibenzo- <i>p</i> -dioxins and furans

Other abbreviations

PM _{2.5}	particles with aerodynamic diameter smaller than 2.5 μm
TSP	total suspended particles
TCLP	Toxic Characteristic Leaching Procedure

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